Turbulent Axisymmetric Near-Wake at Mach Four with Base Injection

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Nomenclature

A = cross-sectional area of base
H = mass-bleed parameter, $\dot{M}(RT_0)^{1/2}/P_0Ak^{1/2}$
I = mass injection parameter, $\dot{M}/\rho_\infty u_\infty A$
k = ratio of specific heats
$\dot{M}$ = mass injection rate
p_b = base pressure
p_{b0} = zero injection base pressure
p_0 = freestream stagnation pressure
p_∞ = freestream pressure
R = gas constant
T_0 = freestream stagnation temperature

Introduction

FROM the early experiments by Cortright and Schroeder,[1] and the theoretical and experimental investigation by Korst, Page, and Childs,[2] it was apparent that the base drag of supersonic vehicles could be controlled effectively by the injection of small quantities of gas into the turbulent near-wake. Experimental investigations of the effect of mass injection into the turbulent near-wake of axisymmetric bodies with blunt bases have been reported in Refs. 1 and 3–7. Most of these previous investigations have been hampered either by model support effects (cf. Refs. 1,4), or by inconsistent zero mass injection data (cf. Refs. 5–7). As a consequence of this apparent lack of detailed data, particularly at Mach numbers higher than two, a systematic investigation of base pressure variation caused by mass injection into a turbulent supersonic axisymmetric near-wake was conducted. The major results of this study are summarized in this Note.

Apparatus

The present experimental investigation was conducted in the Rutgers Axisymmetric Near-Wake Tunnel (RANT),[8] which is an annular-nozzle facility specifically designed to study turbulent, axisymmetric near-wakes in the absence of any model support interference. All tests were conducted at a steady-state stagnation pressure of 152.2 psia ± 0.5 psia, and stagnation temperature of 520°R ± 10°R. The corresponding freestream Mach number and Reynolds number were 3.88 and 1.56 × 10⁷/ft, respectively. The approaching boundary layer was fully turbulent, and the boundary-layer thickness to base diameter ratio was 0.115.

Using metered atmospheric air as the injectant, data were taken for three axial injection schemes and two porous base injection schemes. Axial injection is defined as mass injection through a circular orifice, which is centered on the blunt axisymmetric base. The values of the ratio of orifice diameter to base diameter was d_j/d_b = 0.17, 0.40, and 0.88, respectively. The two smaller orifices were preceded by a subsonic nozzle, while the largest orifice was preceded by a subsonic diffuser. The porous injection data were obtained using two base caps, one having a porosity of 20 microns and the other having a porosity of 100 microns. Since the recirculation region temperature was approximately equal to the temperature of the injectant, no condensation occurred in the near-wake, nor was there any indication of condensation in the visible far-wake.

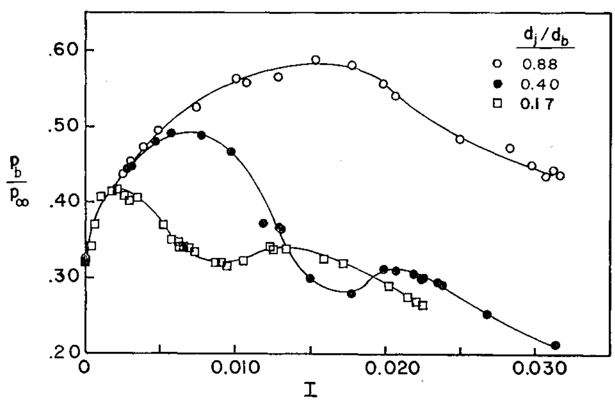

Fig. 1 Axial injection results.

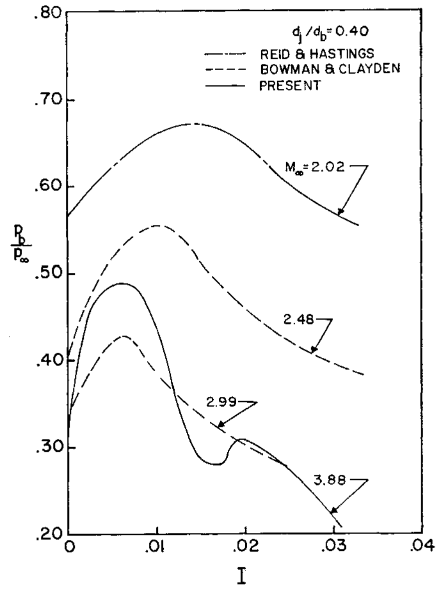

Fig. 2 Base pressure ratio for constant jet/base diameter ratio.

Results

Detailed measurements[8] have shown that the average ratio of the base pressure to the freestream static pressure may be used to characterize the base drag. For zero mass injection in the present tests, this ratio was 0.311, which is consistent with the correlation of other available axisymmetric base pressure data reported by Przirembel and Page.[9]

The present data for the three axial injection schemes are presented in Fig. 1. These results support the conclusion first drawn by Reid and Hastings,[3] that the most efficient means of raising the base pressure for a given mass flow rate is to inject the fluid at the lowest velocity. Furthermore, it can be seen that a distinct, second maximum base pressure exists for the axial schemes, in which the injection orifices are preceded by a subsonic nozzle. However, this second maximum is substantially lower than the first maximum. Schlieren photographs of the near-wake indicated a significant change in the shock structure associated with the axial jet at each inflection point of the two curves.

For the axial injection scheme in which the ratio of jet diameter to base diameter d_j/d_b is 0.40, the present results are compared with other available data in Fig. 2. In the investigations of Reid and Hastings,[3] and Bowman and Clayden,[4] the injection orifice was preceded by a conical Mach 2.0 nozzle. It is apparent that the geometry of the

Received July 15, 1970; revision received August 19, 1970. Research sponsored by the Air Force Office of Scientific Research, Office of Aerospace Research, U.S. Air Force, under contract F44620-68-C-0018.

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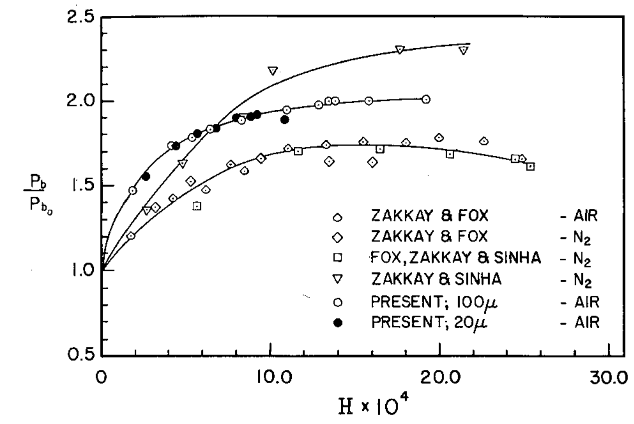

Fig. 3 Porous base injection at Mach 4.0.

injection duct has a very significant influence on the variation of base pressure with mass injection flow rate, because the second maximum is only found for the subsonic nozzle injection case. This second maximum should not be confused with the increase of base pressure at very large mass injection rates as described by Reid and Hastings.[3] Another possible indication of the injection duct influence is that, although the zero mass injection base pressures are decreasing with increasing free stream Mach number in accordance with Ref. 9, the maximum base pressure with mass injection does not follow this trend consistently.

Based on the above results, it is apparent that the most effective injection technique is to introduce the secondary fluid through a porous plate which covers the whole base of the axisymmetric body. The present results for this configuration are compared with other available data in Fig. 3. For all four experiments, the nominal free stream Mach number was 4.0, and the approaching boundary layer was turbulent. However, the reference base pressure ratios varied significantly. Specifically, Zakkay and Fox,[5] Fox, Zakkay, and Sinha,[6] and Zakkay and Sinha,[7] using the same wind tunnel and essentially the same test conditions, reported values of the base pressure at zero mass injection of 0.413, 0.435, and 0.357, respectively. According to Sinha,[10] the results of Refs. 5 and 6 may have been affected by possible nonuniformities in the approaching freestream and misalignment of the streamlined centerbody.

The present data show that the base pressure can be increased by 100% of its sealed base value with mass injection. For an actual vehicle, this would provide for a substantial decrease of the base drag contribution to the total drag. However, before these data can be considered for design calculations, the previously mentioned discrepancies in the reference base pressure values must be resolved.

The present data, as well as that in Refs. 4–6 and 7, show an initial monotonic increase of base pressure with increasing mass flow. However, contrary to the speculation of Bowman and Clayden,[4] the base pressure reaches a plateau value, and then decreases with further increases in the mass injection rate. Measurements at very large mass flow rates were reported by Zakkay and Sinha.[7] As can be seen from Fig. 3, the influence of injection plate porosity on the base pressure is negligible.

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Time-Dependent Solutions of Nonequilibrium Nozzle Flows—A Sequel

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THE solution of steady-state, nonequilibrium, quasi-one-dimensional nozzle flows by means of a numerical, time-dependent technique is described in Ref. 1. This analysis employed a Taylor's series to obtain the flowfield variables in steps of time, starting with assumed initial distributions throughout the nozzle

$$g(x,t + \Delta t) = g(x,t) + (\partial g/\partial t)_t \Delta t + (\partial^2 g/\partial t^2)_t \Delta t^2/2 \quad (1)$$

where g can be any dependent variable such as ρ, T, u, etc., and where the time derivatives are evaluated at time t. The steady-state solution, which is the desired result, is approached at large times. The advantages of this approach, as well as the details of the analysis, are described in Ref. 1; hence, no further elaboration will be given here. However, emphasis is made that Eq. (1), containing three terms of the Taylor's series, is of the second-order accuracy, and that the second-order term is absolutely necessary for stability.

This Note, which is a sequel to Ref. 1, describes the application of a new time-dependent, finite-difference scheme which employs only the first two terms of a series expansion in time,

$$g(x,t + \Delta t) = g(x,t) + (\partial g/\partial t)_{\text{ave}} \Delta t \quad (2)$$

Here, the time derivative is not evaluated at time t as previously; rather, an average value between t and $(t + \Delta t)$ is utilized. This average value is obtained from the general method of MacCormack,[2] who has shown that the general scheme is of second-order accuracy.‡ This new scheme, ap-

Received July 13, 1970; revision received September 14, 1970. This work was supported by the NOL Independent Research funds.

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‡ Acknowledgment is gratefully made to G. Moretti, Polytechnic Institute of Brooklyn, who brought MacCormack's scheme to the author's attention.